

SHORT STRINGS AND NEW PHYSICS PERSPECTIVES IN QCD ¹

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Abstract

Within the (dual) Abelian Higgs model, confining strings do not disappear at small distances but rather become short strings. In compact 3D electrodynamics, as we argue here, the confining strings are also manifested at small distances in unusual power corrections, disobeying the standard rules of the Operator Product expansion. In the most interesting case of QCD, there is yet no derivation of short strings and we turn to phenomenology to find evidence pro or contra their existence. The short strings in QCD lead to non-standard power corrections. A tentative conclusion of the analysis of existing data, both in numerical simulations and in real experiments, is that the novel power corrections are present, at least at the mass scale of $(1 \div 2)$ GeV.

1 Introduction.

The strings which are responsible for confinement in the infrared region can survive [1] in the ultraviolet region as well and be responsible for non-perturbative effects at small distances. The simplest manifestation of the short strings in QCD would be a stringy piece in the heavy quark–antiquark potential at *small* distances:

$$V(r) = -\alpha/r + \sigma_0 r, \quad r \rightarrow 0 \tag{1}$$

This linear piece could be related to divergences of the perturbative series in large orders revealed by the so called ultraviolet renormalon (see [2] and references therein). In this sense,

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one can speculate that the short strings is a non-perturbative counterpart of the ultraviolet renormalon.

It is of course far from being trivial to find the non-perturbative potential at short distances in QCD. Thus, we are invited to consider simpler model with confinement. So far, only the Abelian Higgs model has been analyzed and the stringy potential at short distances was indeed found [1]. The physics behind the stringy potential is highly non-trivial and can be viewed as a manifestation of the Dirac strings. It is worth mentioning that the physical manifestations of the Dirac strings were found first in the example of the compact photodynamics [3]. In Sect. 2 we review the results obtained in the case of the Abelian Higgs model and comment on the connections with the compact $U(1)$. In Sect. 3 we consider the potential at short distances within another $U(1)$ model, namely the compact 3D electrodynamics. As is well known, it exhibits confinement of the electric charges [4], i.e. the linear potential at large distances. We do find a non-analytic behavior of the potential at short distances. However, as is argued in Sect. 4, the new non-analytical terms may disappear once the distance r is much smaller than the size of monopoles present in the model. All the consideration here is on the classical level.

In case of QCD the use of the lattice regularization assumes that the Dirac strings are allowed and carry no action. From this point of view the situation is a reminiscent of the Abelian models mentioned above. However, unlike the abelian case the monopoles associated with the end points of the Dirac string may have zero action. Thus, both classical field configurations and the quantum running of the effective coupling seem to be equally important in the QCD case. As a result, there is no definite prediction for the short distance behavior of the potential at the moment. We concentrate therefore, on phenomenological manifestations of the hypothetical short strings. A comparison with existing data indicates that the novel effects corresponding to the short strings are indeed present. Naturally enough, the data refer to a limited range of distances. Thus, the statement above refers to distances of order $(0.5 \div 1.0)\text{GeV}^{-1}$. The QCD phenomenology is reviewed in Sects. 5,6 while in Sect. 7 conclusions are given.

2 Short Strings in the Dual Abelian Higgs Model.

The first example of drastic non-perturbative effects in ultraviolet was in fact given in paper [3]. The Lagrangian considered is that of free photons:

$$L = \frac{1}{4e^2} F_{\mu\nu}^2 \quad (2)$$

where $F_{\mu\nu}$ is the field strength tensor of the electromagnetic field. Although the theory looks absolutely trivial, it is not the case if one admits the Dirac strings. Naively, the energy associated with the Dirac strings is infinite:

$$E_{\text{Dirac string}} = \frac{1}{8\pi} \int d^3r \mathbf{H}^2 \sim l \cdot A \left(\frac{\text{magnetic flux}}{A} \right)^2 \rightarrow \infty \quad (3)$$

where l, A are the length and area of the string, respectively. Since the magnetic flux carried by the string is quantized and finite the energy diverges quadratically in the ultraviolet, i.e. in the limit $A \rightarrow 0$. However within the lattice regularization the action of the string is in fact zero because of the compactness of the $U(1)$. The invisible Dirac strings may end up with monopoles which have a non-zero action. Moreover, the monopole action is linearly divergent in ultraviolet. However the balance between the suppression due to this action and enhancement due to the entropy factor favors a phase transition to the monopole condensation at $e^2 \sim 1$. As a result the test electric charges are subject to linear potential at all the distances if e^2 is large enough.

Thus, in compact $U(1)$ model the non-perturbative effects change the interaction at all distances, for a range of the coupling values. Next, one considers the Dual Abelian Higgs Model with the action

$$S = \int d^4x \left\{ \frac{1}{4g^2} F_{\mu\nu}^2 + \frac{1}{2} |(\partial - iA)\Phi|^2 + \frac{1}{4} \lambda (|\Phi|^2 - \eta^2)^2 \right\}, \quad (4)$$

here g is the magnetic charge, $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$. The gauge boson and the Higgs are massive, $m_V^2 = g^2 \eta^2, m_H^2 = 2\lambda \eta^2$. There is a well known Abrikosov-Nielsen-Olesen (ANO) solution to the corresponding equations of motion. The dual ANO string may end up with electric charges. As a result, the potential for a test charge-anticharge pair grows linearly at large distances:

$$V(r) = \sigma_\infty r, \quad r \rightarrow \infty. \quad (5)$$

Note that there is a Dirac string resting along the axis of the ANO string connecting monopoles and its energy is still normalized to zero.

An amusing effect occurs if one goes to distances much smaller than the characteristic mass scales $m_{V,H}^{-1}$. Then the ANO string is peeled off and one deals with a naked (dual) Dirac string. The manifestation of the string is that the Higgs field has to vanish along a line connecting the external charges. Otherwise, the energy of the Dirac string would jump to infinity anew.

As a result of the boundary condition that Φ vanishes on a line connecting the charges, the potential contains a stringy piece (1) at short distances [1]. The string tension σ_0 smoothly depends on the ratio m_H/m_V . In particular, in the Bogomolny limit ($m_H = m_V$) the string tension

$$\sigma_0 \approx \sigma_\infty, \quad (6)$$

i.e. the effective string tension is the same at all distances.

3 Short Strings in 3D Compact Electrodynamics.

As it is well known [4] in 3D compact electrodynamics the charge-anticharge potential is linear at large separations. Below we consider the string tension σ_0 at small distances and show that it has a non-analytical piece associated with small distances.

As usual, it is convenient to perform the duality transformation, and work with the corresponding Sine-Gordon theory. The expectation value of the Wilson loop in dual variables

is:

$$W = \frac{1}{\mathcal{Z}} \int \mathcal{D}\chi e^{-S(\chi, \eta_C)}, \quad (7)$$

where

$$S(\chi, \eta_C) = \left(\frac{e}{2\pi}\right)^2 \int d^3x \left\{ \frac{1}{2}(\vec{\partial}\chi)^2 + m_D^2(1 - \cos[\chi - \eta_C]) \right\}, \quad (8)$$

m_D is the Debye mass and $S(\chi, 0)$ is the action of the model. If static charge and anticharge are placed at the points $(-R/2, 0)$ and $(R/2, 0)$ in the x_1, x_2 plane (x_3 is the time axis), then

$$\eta_C = \arctg\left[\frac{x_2}{x_1 - R/2}\right] - \arctg\left[\frac{x_2}{x_1 + R/2}\right], \quad -\pi \leq \eta_C \leq \pi. \quad (9)$$

Below we present the results of the numerical calculations of the string tension,

$$\sigma = \partial E / \partial(m_D R), \quad (10)$$

$$E = \int d^2x \left\{ \frac{1}{2}(\vec{\partial}\chi)^2 + m_D^2(1 - \cos[\chi - \eta_C]) \right\}. \quad (11)$$

Note that the energy E is measured now in units of the dimensional factor $(\frac{e}{2\pi})^2$ (*cf.* (8)). Variation of functional (11) leads to the equation of motion $\Delta\chi = m_D^2 \sin[\chi - \eta_C]$. For finite R we can solve this equation numerically. The energy E versus $m_D R$ is shown on Fig.1(a). At large separations between the charges ($m_D R \gg 1$) it tends to the asymptotic linear behavior $E = 8m_D R$ which can be obtained also analytically [4]).

At small distances there is a contributions of Yukawa-type to the energy (11), which should be extracted explicitly. Note that in course of rewriting original 3D compact electrodynamics in the form (7-8) the Coulomb potential was already subtracted, so that (11) contains Yukawa-like piece without singularity at $R = 0$. It is not difficult to find the corresponding coefficient:

$$E = E^{string} - 2\pi(K_0[m_D R] + \ln[m_D R]) \quad (12)$$

where $K_0(x)$ is the modified Bessel function and E^{string} is the energy of the charge-anticharge pair. The corresponding string tension

$$\sigma^{string} = \sigma + 2\pi(-K_1[m_D R] + \frac{1}{m_D R}) \quad (13)$$

is shown on Fig.1(b). We found that the best fit of numerical data for small values of $m_D R$ is by the function $\sigma^{string} = const \cdot (m_D R)^\nu$ which gives $\nu \approx 0.6$.

Thus the non-analytical potential associated with small distances is softer than in the case of the Abelian Higgs model. The source of the non-analyticity is the behavior of the function $\eta_C(x_1, x_2)$ (9) which is singular along the line connecting the charges, see Fig.2(a).

4 Georgi-Glashow model

The compact electrodynamics is usually considered as the limit of Georgi-Glashow model, when the radius of the 't Hooft - Polyakov monopole tends to zero. For a non-vanishing

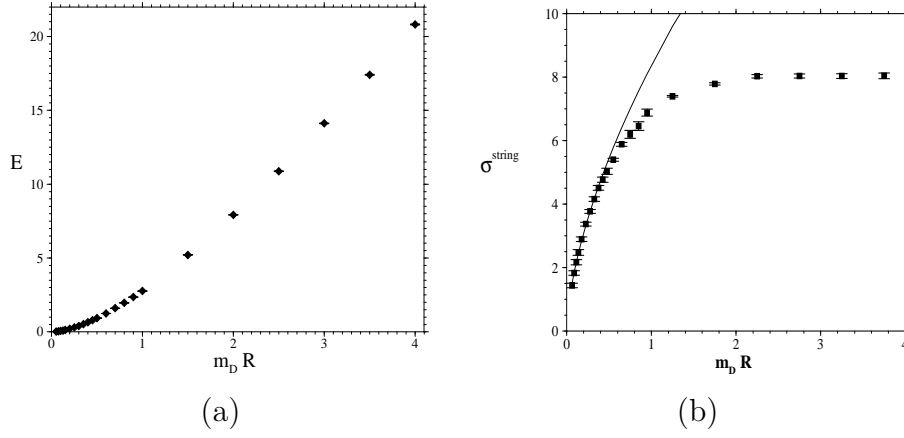


Figure 1: (a) The string tension (10) of the charge – anticharge separated by the distance R in 3D compact U(1) theory; (b) The string tension σ^{string} (13) as a function of $m_D R$ with corresponding best fitting function (see text).

monopole size the problem of evaluating the potential at small distances becomes rather complicated. To avoid unnecessary further complications we consider the 3D Georgi–Glashow model in the BPS limit. The 't Hooft Polyakov monopole corresponds then to the fields:

$$\Phi^a = \frac{x^a}{r} \left(\frac{1}{\tanh(\mu r)} - \frac{1}{\mu r} \right), \quad (14)$$

$$A_i^a = -\varepsilon^{aic} \frac{x^a}{r} \left(\frac{1}{r} - \frac{\mu}{\sinh(\mu r)} \right), \quad A_0^a = 0. \quad (15)$$

The contribution of this monopole to the *full non-Abelian* Wilson loop W can be calculated analytically. If the static charges are placed at points $\pm \vec{R}/2$ in the x_1, x_2 plane the result is:

$$W(\vec{b}_1, \vec{b}_2, \mu) = \cos h(\mu b_1) \cos h(\mu b_2) + \frac{(\vec{b}_1 \cdot \vec{b}_2)}{b_1 b_2} \sin h(\mu b_1) \sin h(\mu b_2), \quad (16)$$

here $\vec{b}_{1,2} = \vec{x}_0 \pm \vec{R}/2$, $b_k = |\vec{b}_k|$, \vec{x}_0 is the center of the 't Hooft – Polyakov monopole and

$$h(x) = \frac{\pi}{2} - \frac{x}{2} \int_{-\infty}^{+\infty} \frac{d\zeta}{\sqrt{x^2 + \zeta^2} \sinh \sqrt{x^2 + \zeta^2}}. \quad (17)$$

One way to represent (16) in terms of the function $\eta_{\mathcal{C}}$ introduced earlier is:

$$\eta_{\mathcal{C}}(x_0, R, \mu) = \text{sign}(y) \arccos W(\vec{b}_1, \vec{b}_2, \mu). \quad (18)$$

In the limit $R\mu \rightarrow \infty$ $W(\vec{b}_1, \vec{b}_2, \mu) \rightarrow \cos \eta_{\mathcal{C}}$ and $\eta_{\mathcal{C}}(x_0, R, \mu)$ coincides with the definition (9). For small $R\mu$, $\eta_{\mathcal{C}}$ is singular not only between external charges, but also outside this region (see Fig.2(b)) although the strength of singularity gets smaller. In the limit of vanishing $\eta_{\mathcal{C}}$ σ_0 should vanish.

To summarize, it is natural to expect that at distances much smaller than the monopole size, the non-analytical piece in the potential associated with small distances disappears. However, for a consistent treatment of the problem one should take into account the modification of the Coulomb-like monopole interaction due to the finite size of the BPS monopoles.

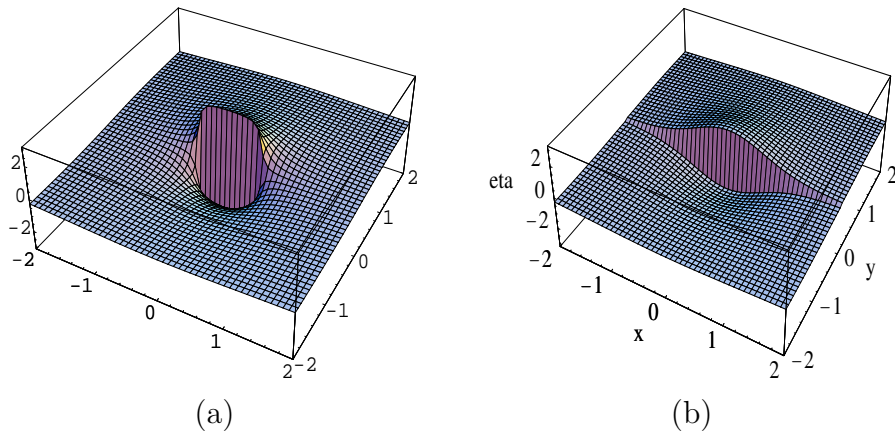


Figure 2: Function η_C in compact $U(1)$ theory (a) and for extended monopoles (b), eq. (18)

5 Topological defects and short-distance potential in QCD.

Knowing the physics of the Abelian models above it is easy to argue that the perturbative vacuum of QCD is not stable in fact. Indeed, let us make the lattice more coarser a la Wilson until the effective coupling of QCD would reach the value where the phase transition in the compact $U(1)$ occurs. Then the QCD perturbative vacuum is unstable against the monopole formation. The actual non-perturbative vacuum can of course be very different but it cannot remain perturbative. Similar remark with respect to formation of Z_2 vortices was in fact made long time ago [7].

Thus, it is natural to expect that singular non-perturbative defects play a role in QCD as well. In case of the abelian projection these are Dirac strings with monopoles at the ends, while in case of the Z_2 vortices the corresponding infinitely thin objects can be identified with the so called P-vortices, see [8] and references therein.

The existence of the infinitely thin topological defects in QCD makes it close akin of the Abelian models considered above. However, the non-Abelian nature of the interaction brings in an important difference as well. Namely, the topological defects in QCD are marked rather by singular potentials than by a large non-Abelian action. Consider first the Dirac string.

Introduce to this end a potential which is a pure gauge:

$$A_\mu = \Omega^{-1} \partial_\mu \Omega \quad (19)$$

and choose the matrix Ω in the form:

$$\Omega(x) = \begin{pmatrix} \cos \frac{\gamma}{2} & \sin \frac{\gamma}{2} e^{-i\alpha} \\ -\sin \frac{\gamma}{2} e^{i\alpha} & \cos \frac{\gamma}{2} \end{pmatrix} \quad (20)$$

where α and γ are azimuthal and polar angles, respectively. Then it is straightforward to check that we generated a Dirac string directed along the x_3 -axis ending at $x_3 = 0$ and carrying the color index $a = 3$. It is quite obvious that such Abelian-like strings are allowed by the lattice regularization of the theory.

The crucial point, however, is that the non-Abelian action associated with the potential (19) is identical zero. On the other hand, in its Abelian components the potential looks as a Dirac monopole, which are known to play important role in the Abelian projection of QCD (for a review see, e.g., [9]). Thus, there is a kind of mismatch between short- and large-distance pictures. Namely, if one considers the lattice size $a \rightarrow 0$, then the corresponding coupling $g(a) \rightarrow 0$ and the solution with a zero action (19) is strongly favored at short distances. At larger distances we are aware of the dominance of the Abelian monopoles which have a non-zero nonabelian action [10]. The end-points of a Dirac string still mark centers of the Abelian monopole. Thus, monopoles can be defined as point-like objects topologically in terms of singular potentials, not action.

Similar logic holds in case of the so called P-vortices as well. To detect the P-vortices one uses [8] the gauge maximizing the sum

$$\sum_l |Tr U_l|^2 \quad (21)$$

where l runs over all the links on the lattice. The center projection is obtained by replacing

$$U_l \rightarrow \text{sign} (Tr U_l). \quad (22)$$

Each plaquette is marked either as (+1) or (-1) depending on the product of the signs assigned to the corresponding links. P-vortex then pierces a plaquette with (-1). Moreover, the fraction p of the total number of plaquettes pierced by the P-vortices and of the total number of all the plaquettes N_T , obeys the scaling law

$$p = \frac{N_{vor}}{N_T} \sim f(\beta) \quad (23)$$

where the function $f(\beta)$ is such that p scales like the string tension. Assuming independence of the piercing for each plaquette one has then for the center-projected Wilson loop W_{cp} :

$$W_{cp} = [(1-p)(+1) + p(-1)]^A \approx e^{-2pA} \quad (24)$$

where A is the number of plaquettes in the area stretched on the Wilson loop. Numerically, Eq. (24) reproduces the full string tension.

It is quite obvious that the P-vortices defined this way correspond in the continuum limit to singular gauge potentials A_μ^a (see, e.g., [1]). Indeed, the link matrices with the negative trace correspond in the limit of the vanishing lattice spacing, $a \rightarrow 0$ to the gauge potentials A_μ^a of the order $\frac{1}{a}$. Thus P-vortices correspond to large gauge potentials. The potentials should mostly cancel, however, if the corresponding field-strength tensors are calculated because of the asymptotic freedom. The logic is essentially the same as outlined above for the Dirac string, see, e.g. [11] and references therein.

At the moment, it is difficult to say a priori whether the topological defects defined in terms of singular potentials can be considered as infinitely thin from the physical point of view. They might well be gauge artifacts. Phenomenologically, using the topologically defined point-like monopoles or infinitely thin P-vortices one can measure non-perturbative

$\bar{Q}Q$ potential at all the distances. It is remarkable therefore that the potentials generated both by monopoles [12] and P-vortices [8] turn to be linear at all the distances:

$$V_{non-pert}(r) \approx \sigma_{\infty} r \text{ at all } r \quad (25)$$

Note that the Coulomb-like part is totally subtracted out through the use of the topological defects. Moreover, no-change in the slope agrees well with the predictions of the dual Abelian Higgs model (see Sect. 2).

The numerical observation (25) is highly nontrivial. If it were only the non-Abelian action that counts, then the non-perturbative fluctuations labeled by the Dirac strings or by P-vortices are bulky (see discussion above) and the corresponding $\bar{Q}Q$ potentials (25) should have been quadratic at short distances r . This happens, for example, in the model [13] with finite thickness of Z_2 vortices. Also, if the lessons from the Georgi–Glashow model apply (see Sect 4 above) the finite size of the monopoles would spoil linearity of the potential at short distances.

To summarize, direct measurements of the non-perturbative $\bar{Q}Q$ potential indicate the presence of a stringy potential at short distances. The measurements go down to distances of order $(2GeV)^{-1}$.

6 QCD phenomenology.

In view of the results of measurements of the non-perturbative potential it is interesting to reexamine [1] the power corrections with the question in mind, whether there is room for novel corrections associated with the short strings. From the dimensional considerations alone it is clear that the new corrections are of order σ_0/Q^2 where Q is a large generic mass parameter characteristic for problem in hand. Also, the ultraviolet renormalons in 4D indicate the same kind of correction. Unlike the case of the non-perturbative potential discussed above, other determinations of the power corrections ask for a subtraction of the dominating perturbative part. Which might make the results less definitive. Here we briefly overview the relevant results.

(i) The first claim of the existence of non-standard $1/Q^2$ corrections was made in ref. [14]. Namely, it was found that the expectation value of the plaquette minus perturbation theory contribution shows $1/Q^2$ behavior. On the other hand, the standard Operator Product expansion results in a $1/Q^4$ correction.

(ii) The lattice simulation [15] do not show any change in the slope of the full $Q\bar{Q}$ potential as the distances are changed from the largest to the smallest ones where Coulombic part becomes dominant. It is known from phenomenological analysis and from the calculations on the lattice [5, 6] that the realistic QCD corresponds to the dual Abelian Higgs model with $m_H \approx m_V$. As is mentioned in Sect.2, the AHM in the classical approximation also gives $\sigma_{\infty} \approx \sigma_0$ at $m_H = m_V$.

(iii) The explicit subtraction of the perturbative corrections at small distances from $Q\bar{Q}$ potential in lattice gluodynamics was performed in ref.[16]. This procedure gives $\sigma_0 \approx 5\sigma_{\infty}$ at very small distances.

(iv) There exist lattice measurements of fine splitting of the $Q\bar{Q}$ levels as function of the heavy quark mass. The Voloshin-Leutwyler [17] picture predicts a particular pattern of the heavy mass dependence of this splitting. Moreover, these predictions are very different from the predictions based on adding a linear part to the Coulomb potential (Buchmuller-Tye potential [18]). The results of recent calculations of this type [19] favor the linear correction to the potential at short distances.

(v) Analytical studies of the Bethe-Salpeter equation and comparison of the results with the charmonium spectrum data favor a non-vanishing linear correction to the potential at short distances [20, 21].

(vi) The lattice-measured instanton density as a function of the instanton size ρ does not satisfy the standard OPE predictions that the leading correction is of order ρ^4 . Instead, the leading corrections is in fact quadratic [22].

(vii) One of the most interesting manifestation of short strings might be $1/Q^2$ corrections to the standard OPE for current-current correlation function $\Pi(Q^2)$. It is impossible to calculate the coefficient of $1/Q^2$ corrections from first principles, and in ref. [23] it was suggested to simulate this correction by a tachyonic gluon mass. The Yukawa potential with an imaginary mass has the linear attractive piece at small distances, i.e. reproduces short strings. The use of the gluon propagator with the imaginary gluon mass ($m_g^2 = -0.5 \text{ GeV}^2$) explains unexpectedly well the behavior of $\Pi(Q^2)$ in various channels. To check the model with a tachyonic short-distance mass further, it would be very important to perform the accurate calculations of various correlators $\Pi(Q^2)$ on the lattice. There are also alternative theoretical schemes in QCD [24] which predict non-conventional $1/Q^2$.

7 Concluding Remarks

As is revealed by analysis of the data on the power corrections, the existence of the novel quadratic corrections is strongly supported by the data. There are, however, two caveats to the statement that the novel short-distance power corrections have been detected. On the theoretical side, the existence of short strings has been proven in only within the Abelian Higgs model. As for the QCD itself, the analysis is so far inconclusive. On the experimental side, the data always refer to a limited range of distances. In particular linear non-perturbative potential has been observed at distances of order of one lattice spacing which is in physical units is $(1 \div 2 \text{ GeV})^{-1}$. One can argue that at shorter distances the behavior of the non-perturbative power corrections changes (see, e.g., [25, 22]). Which would be a remarkable phenomenon by itself.

Acknowledgments

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